Neutrino Detectors

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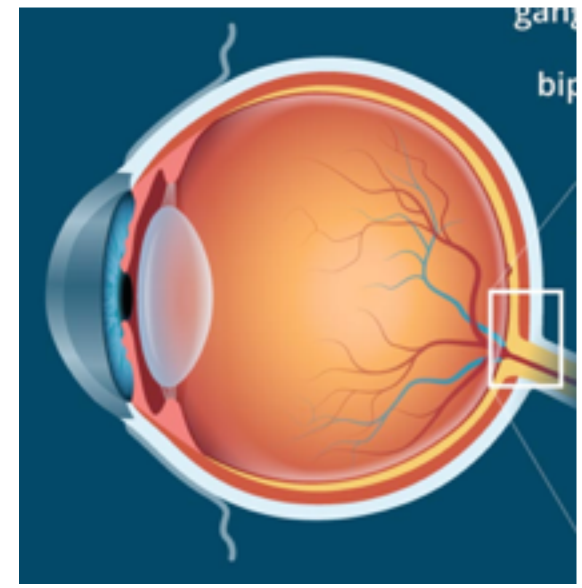
Some Basics

- **We can only measure 4 quantities and their combinations:**
  - **Distance (units are meters)**
  - **Time (units are seconds)**
  - **Mass (units are kilogram)**
  - **Electric Charge (coulomb)**



Example

- **All detectors are built on the principle of charge detection.**
- **Any effect must be first be converted to free electric charge or motion of charge to be detected.**
- **This is regardless of whether detecting light, neutrinos, or gravitational waves.**

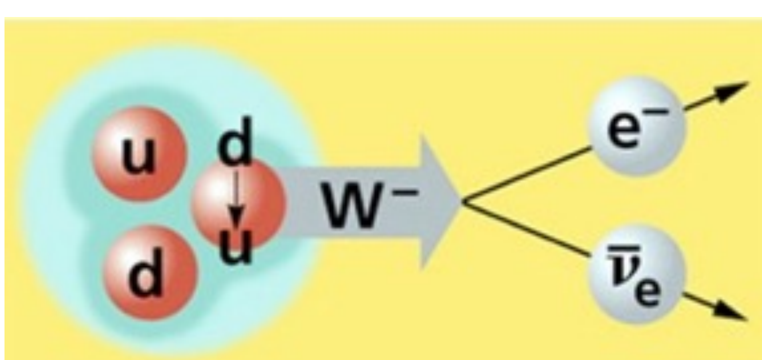
Neutrino Detection

- ***Neutrinos are very light particles with no electrical charge.***
- ***They cannot stick together or to other ordinary things.***
- ***Just like photons, the signature of neutrinos must be first be converted into electrical particles before we can detect them.***
- ***Boris Kayser: there are hundreds of billions of neutrinos passing through us every second. The universe has almost as many neutrinos as particles of light.***

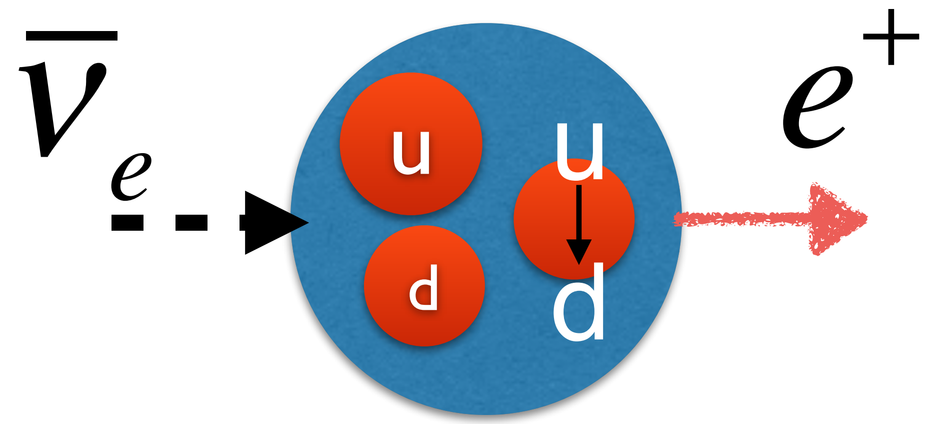
Weak interaction

- ***Radioactivity (beta decay) is a process that converts ordinary charged matter inside nuclei into neutrinos.***
- ***There is "inverse radioactivity" that converts neutrinos into charged particles.***
- ***Both of these are called weak interactions because they are rare.***

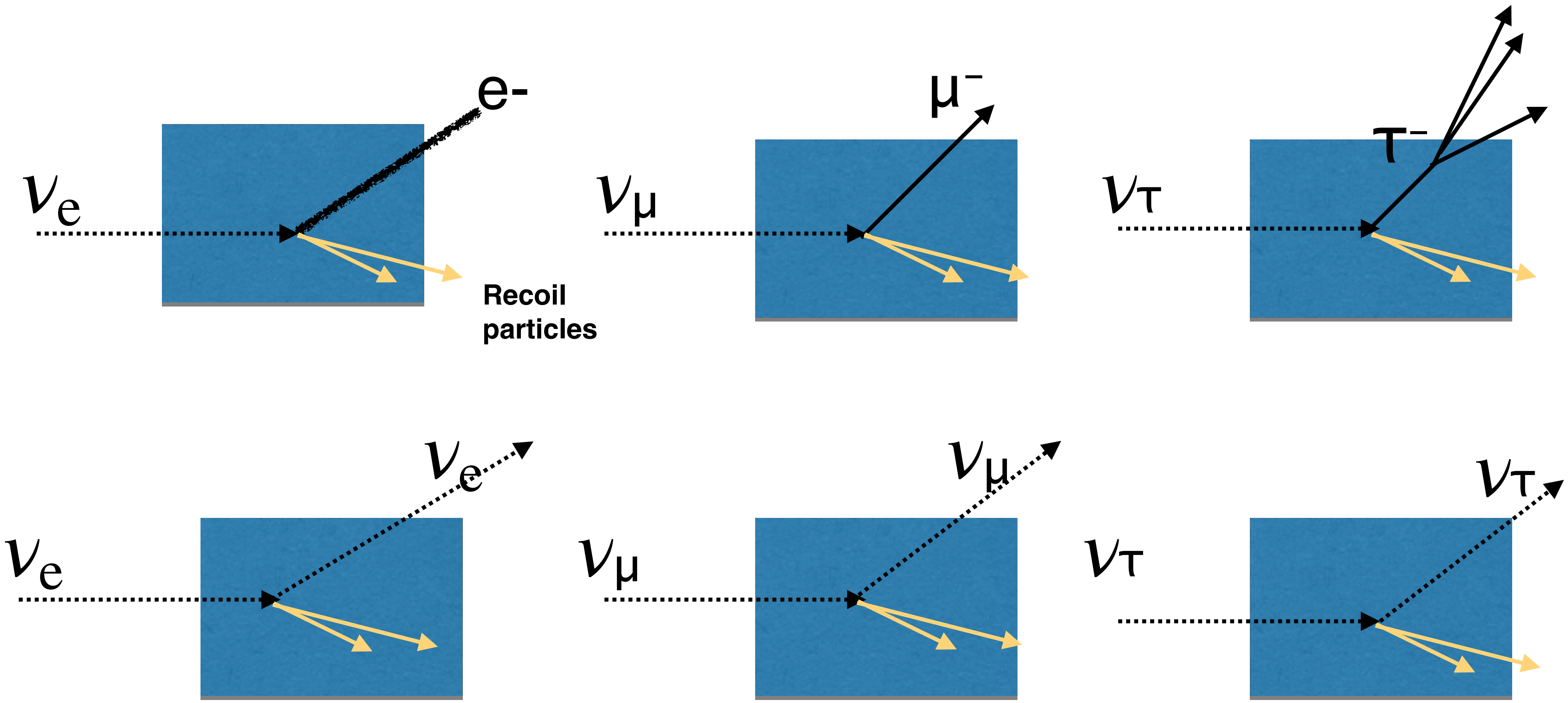
$$n \to p\ e^-\ \bar{\nu}_e$$



$$\bar{\nu}_e + p \to e^+ + n$$

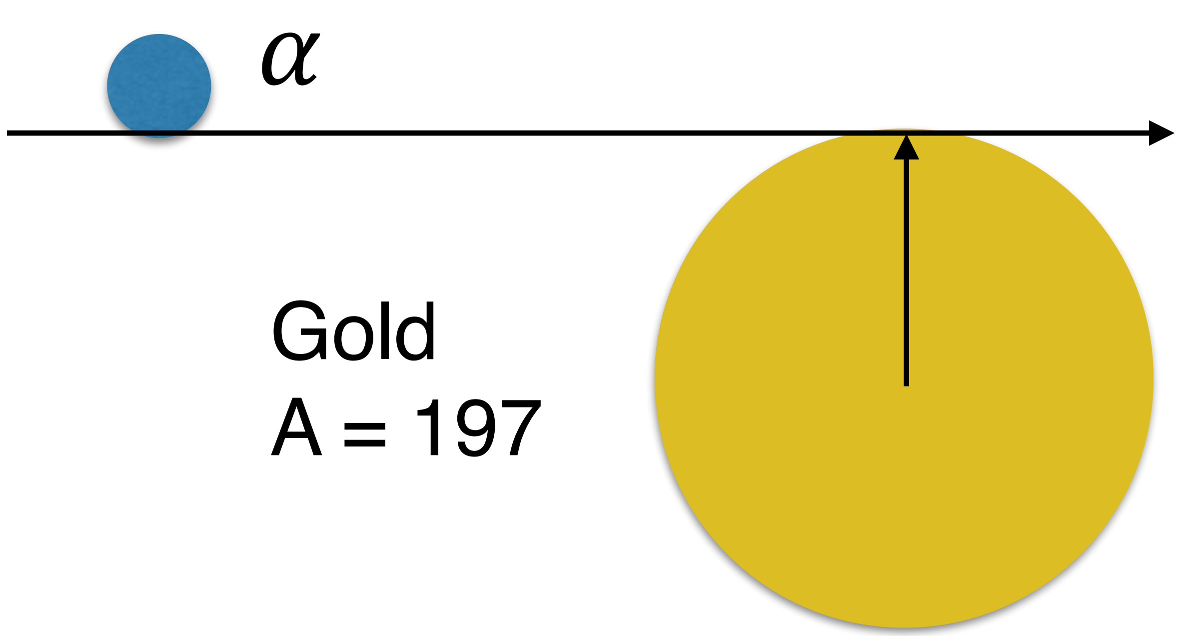


Neutrino Detection for 3 types of neutrinos



- ***<u>The neutrino is invisible as it enters a detector. Rarely interacts and leaves charged particles that can be detected.</u>***
- ***Neutrino collision on atoms in detectors produces a charged lepton. The electron, muon, tau have very different signatures in a detector.***
- ***Neutrino can also collide and scatter away leaving observable charged particles.(Neutral Current)***

Cross section for particle collisions



Radius of a gold nucleus is

$$R = 1.2 \times \sqrt[3]{197}\, fm = 7\, fm$$

fm is $10^{-15} m$

Cross section for alpha particle is then

$$\sigma \approx \pi R^2 \approx 1.5 \times 10^{-24}\, cm^2$$

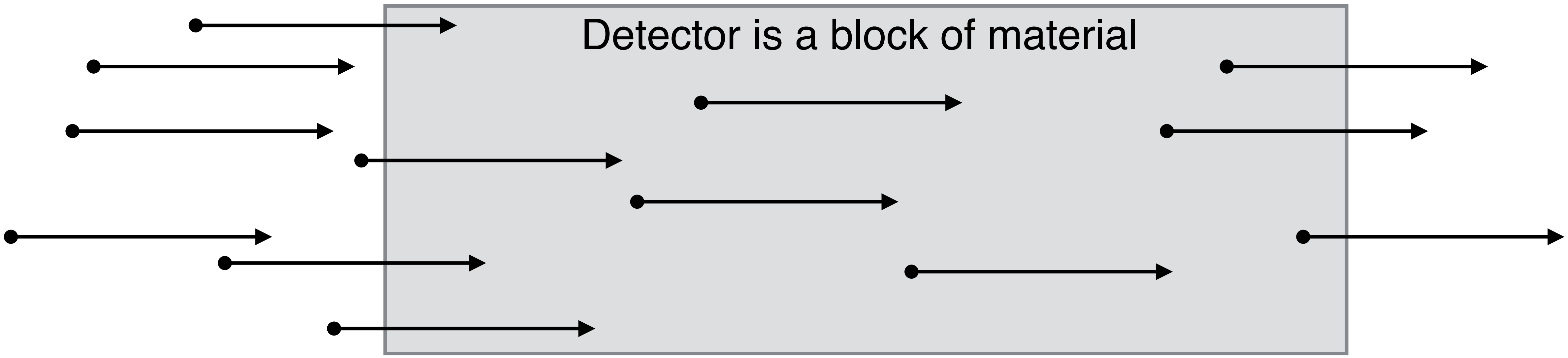
In particle physics, the cross section between any two particles is the area transverse to their relative motion within which they must meet to order to interact. It is the effective size.

More about cross section

- ***Quantum physics is very strange. There are no hard spheres and the cross section depends on many things:***
  - ***The two types of particles. (alpha and Gold …)***
  - ***Their spin orientation if any.***
  - ***Their relative velocities.***
  - ***The type of interaction that they exhibit: electrical, weak, or strong !***

Neutrinos have extremely small cross section. Even for Neutrino on Gold.

Neutrino Cross sections are extremely small compared to alpha on Gold



As particles penetrate material, there is a reduction in the flux (particle/area/sec)

$$F(x) = F(0)e^{-\sigma\rho x}$$

$$\lambda = 1/(\sigma\rho)$$

λ is the mean free path

σ is the cross section

ρ is the density of targets

(In water $\rho \sim 6\times10^{23} cm^{-3}$)

For 1 GeV neutrino interactions $\sigma \sim 10^{-38}$ and

$$\lambda = \frac{1}{10^{-38} \bullet 6\times10^{23}} \approx 10^{12}\, meters!$$

In ordinary matter neutrinos just penetrate through with very rare interactions.

How to calculate neutrino event rate ?

- *Events = Flux ($/cm^2/sec$)*Cross-section(cm^2)*Targets*

- Targets are the number of particle targets in a detector volume. Detector itself serves as the target for interactions.

- 1 ton of anything has ~ 6×10^{29} protons and neutrons and
- 1 ton of anything has ~3×10^{29} electrons
- Typical cross section is 10^{-38} cm^2 x Energy (in billion eV)
- Neutrinos have huge energy range: eV to 10^{15} eV.
- Cross sections for low energies can be extremely small.

- 1 eV = Energy to move 1 electron through 1V=$1.6\ 10^{-19}$Joule

Detector mass needed for 1000 evts/yr ?

$$\varphi = 5000\ m^{-2}\sec^{-1}$$

$$E \sim 1\ GeV$$

$$\sigma \sim 10^{-38}\ cm^{2}$$

$$Nucleons = 6\times 10^{29}\ ton^{-1}$$

$$N = \varphi \bullet \sigma \bullet 6\times 10^{29} \bullet 3\times 10^{7}\ ton^{-1} yr^{-1}$$

$$N = 0.1\ events / ton / yr$$

Example using Atmospheric Neutrinos

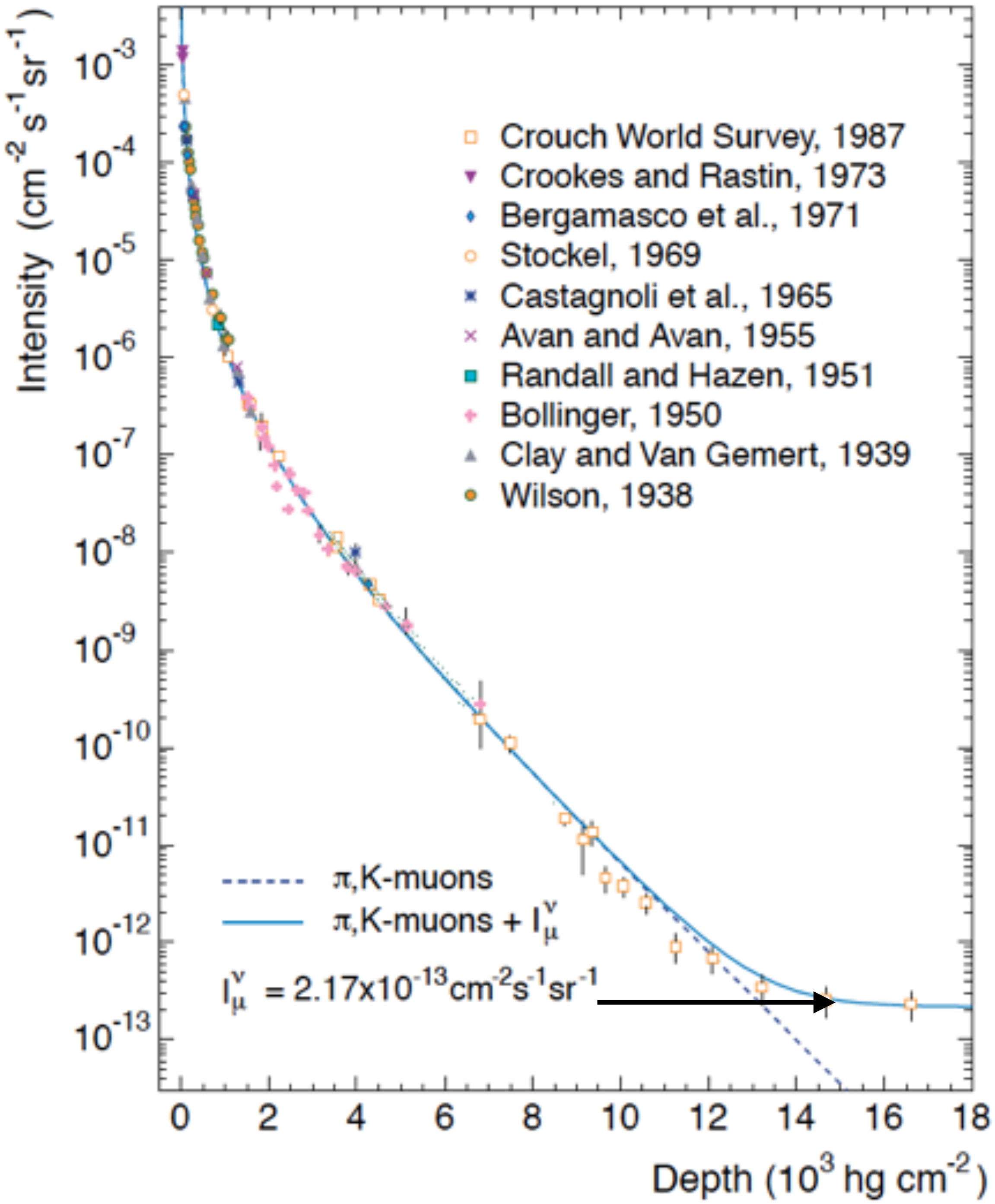
- ***The first most important consideration for neutrino detection is the mass of the detector. (thousands of tons are needed for many experiments).***
- ***If flux is high mass can be lowered.***
- ***Both Energy and Flux need to be known.***

Typical Neutrino Detector Technologies

Material	Composition	Density	Signal type	Comment
Water/Ice	H_2O	1.0	Cherenkov Light	Can be huge
Liquid Scintillator	$\sim CH_2$	~0.9	Scintillation Light	Low energy Threshold
Plastic Scintillator	$\sim CH_2$	~0.9	Scintillation Light	Segmented
Steel planes	Fe	~7.8	Scint./Gas chambers	Magnetized
Liquid Argon	Ar	1.4	Charge/ Scintillation	Can be very fine grained
Radiochemical	Ga, C_2Cl_4 , In	Depends on technololgy	Induced Radioactivity	Extremely Low Thresholds
Water-based Scintillator	$H_2O + \epsilon CH_2$	1.0	Cherenkov + Scint.	Huge with low threshold

Given the emphasis on detector mass, we must choose materials that are inexpensive and produce a signature that can be easily measured by common sensors. There are many clever schemes for sensors.

Cosmic Ray backgrounds

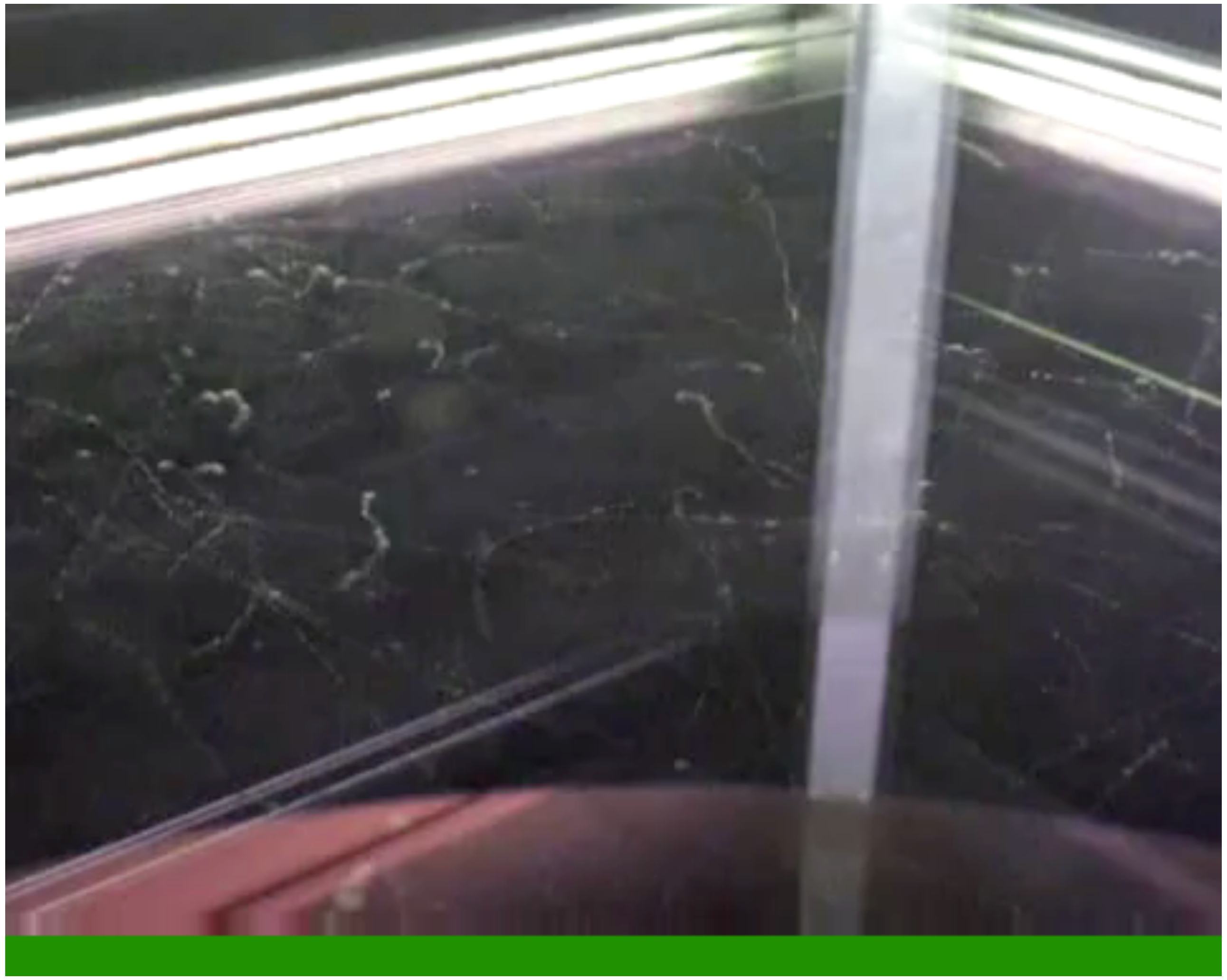


This axis is approximately km of water depth

$$1\,\text{km.w.e} = 10^5\ g\ cm^{-2}\ \text{of standard rock}$$

- ***Central issue in neutrino detection is background from cosmic rays; reduced by overburden or depth.***
- ***The needed depth depends on the physics signals.***
- ***The spectrum of muons at shallow depth is ~few GeV with $Cos^2\theta$ distribution. At surface ~70 Hz/m^2***
- ***Beyond ~2 km, the spectrum is constant around ~300 GeV and the angular distribution becomes steeper.***
- ***For very low energies cosmogenic neutrons are important.***

Let's now look at some data

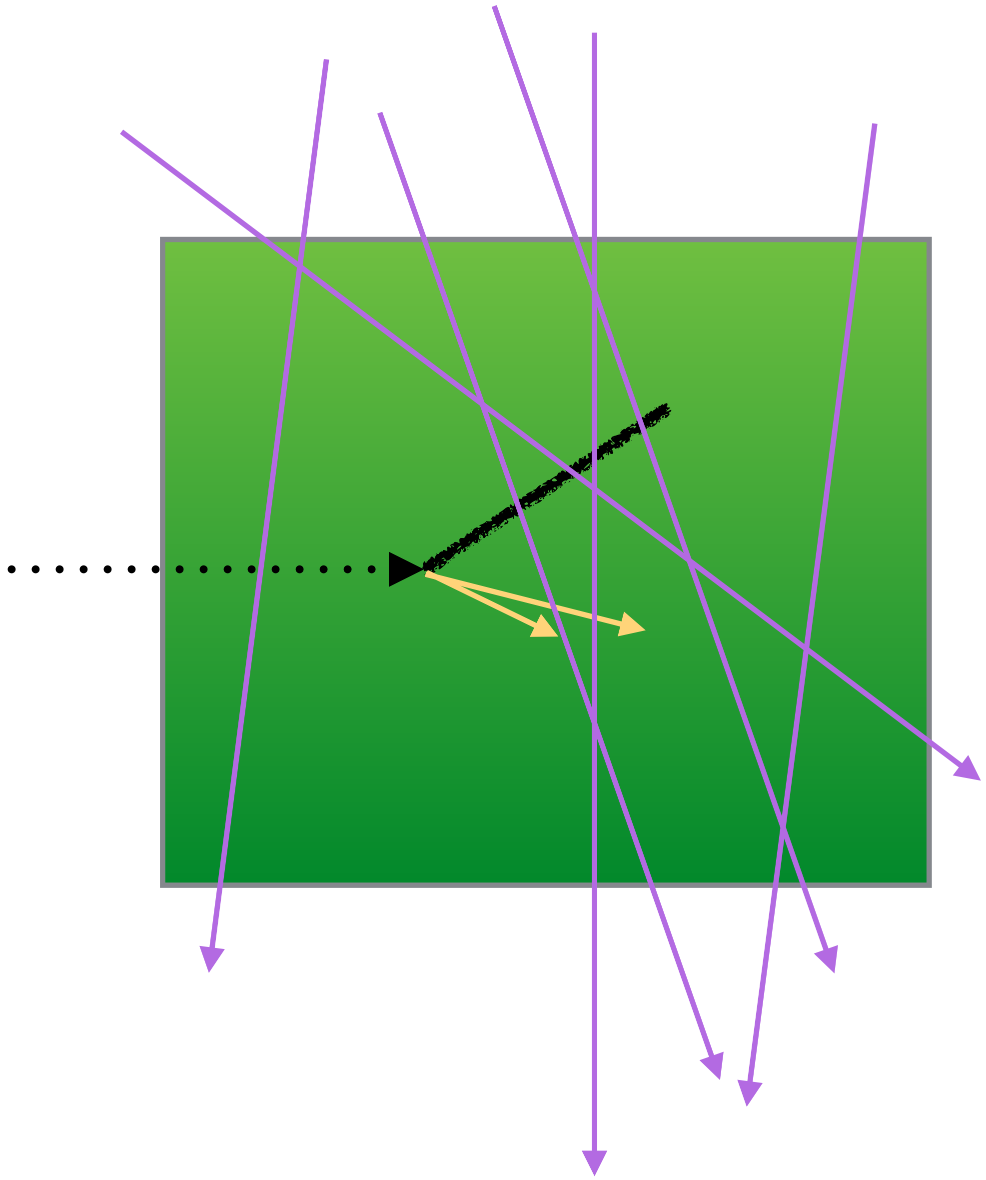


It would be impossible to see a neutrino interaction in this !

Cosmic ray cloud chamber at the New York Hall of Science

The surface rate is ~100 $m^{-2}sec^{-1}sr^{-1}$
Mean ~4 GeV
Flat below 1 GeV. $E^{-2.7}$ above 10 GeV.
Angular ~ Cos^2(Theta)

Summarize so far



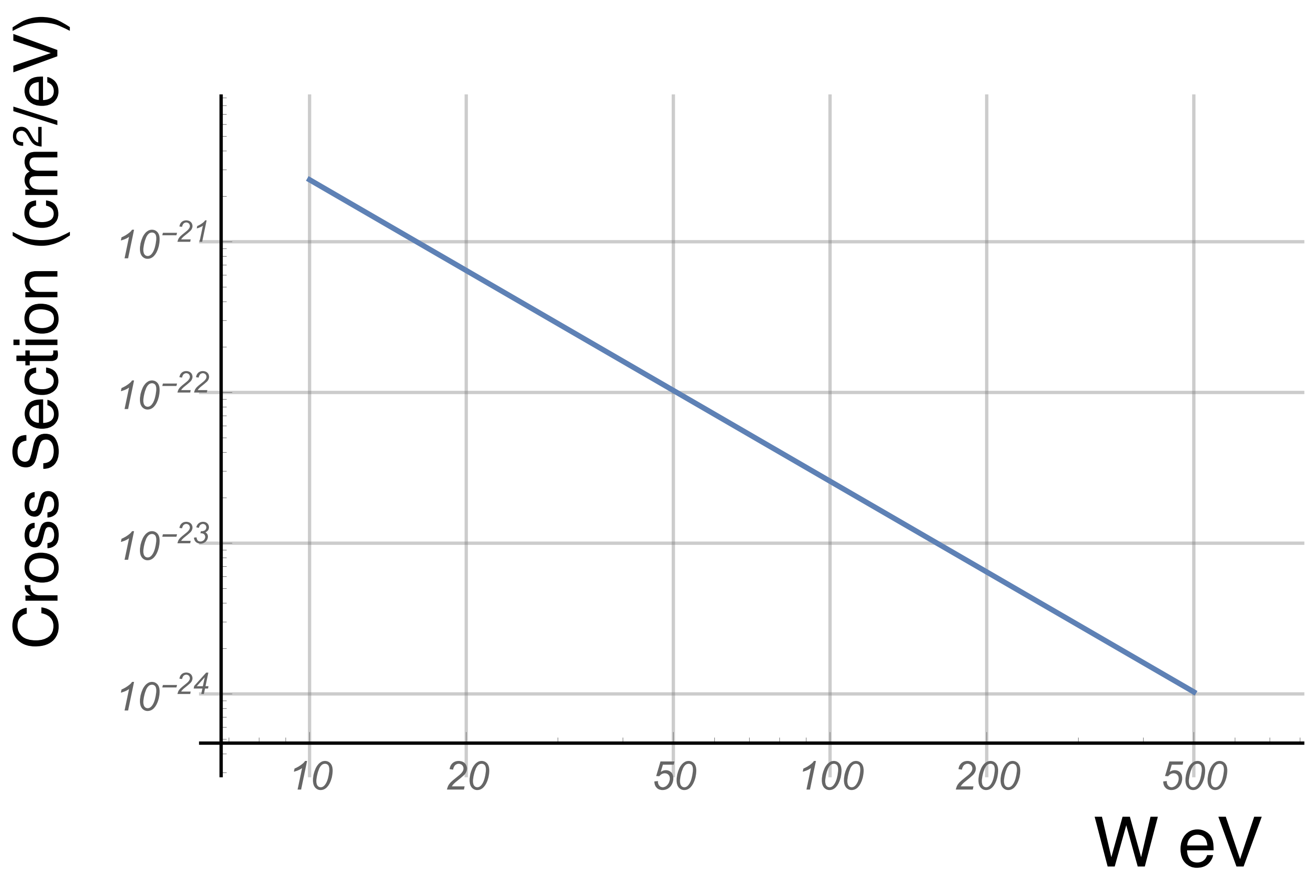
- ***Neutrinos interact in blocks of material and leave energetic charged particles. These are rare events !***
- ***We must find these rare neutrino events in the presence of cosmic rays that penetrate all the time.***
- ***The signature of neutrino interactions are different for different energies and neutrino type.***
- ***How do we register the deposited charged particles in our electronics ?***

Energy Loss

Most of the energy loss of fast charged particles is due to single collisions with atomic electrons. In most collisions energy W is lost with W < 100 eV.

There is a Maximum energy loss in single collision on free electrons.

$$W_{\max} \approx 2m_e\beta^2\gamma^2 / (1 + 2\gamma m_e / M)$$



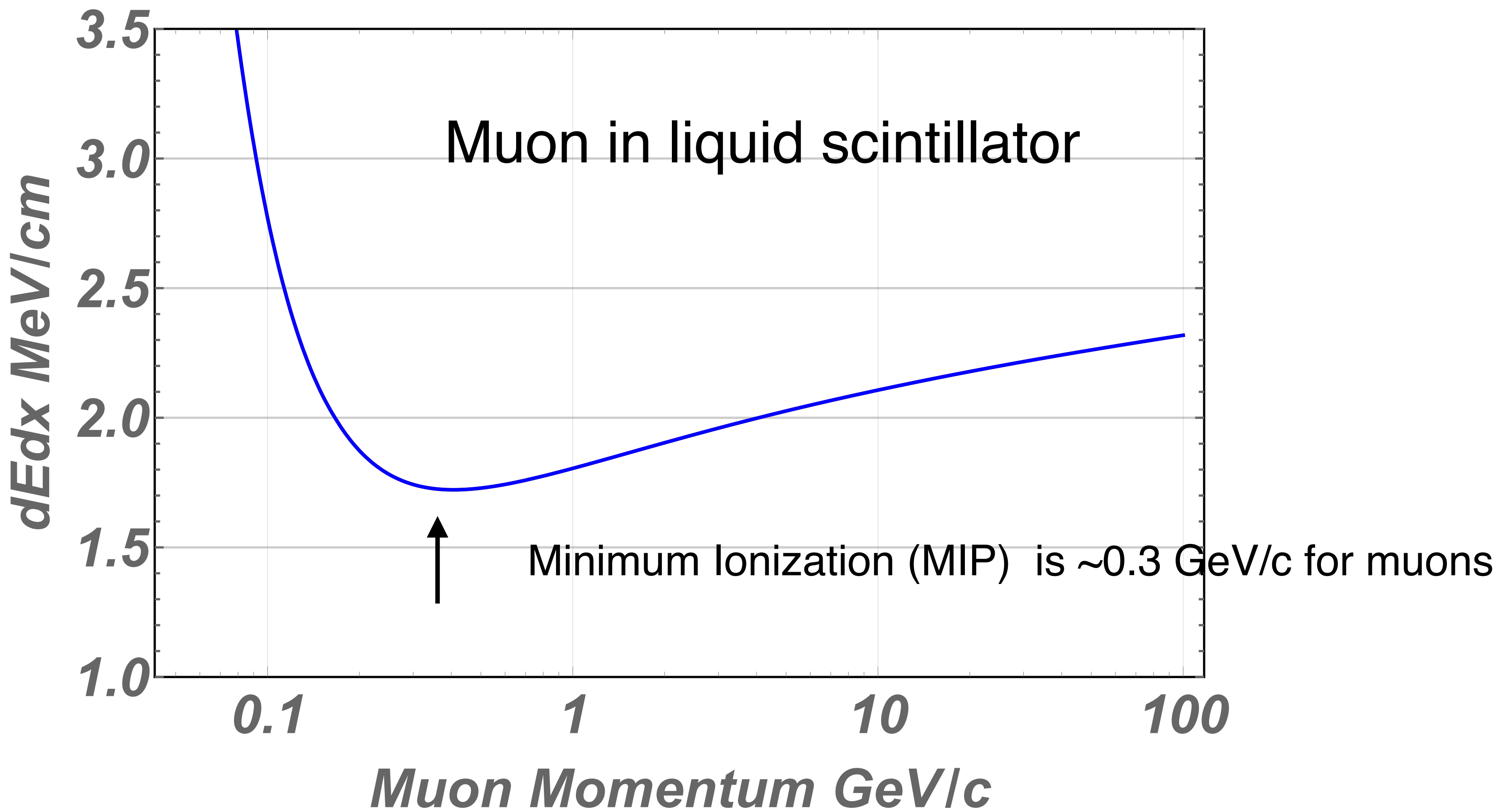
$$\frac{d\sigma(W,\beta)}{dW} = \frac{k_r}{\beta^2}\frac{(1-\beta^2 W / W_{\max})}{W^2}$$

$$k_r = 2\pi r_e^2 m_e z^2 = 2.54955 \times 10^{-19} z^2 \cdot eV \cdot cm^2$$

We know how to calculate and simulate this in great detail in our detectors.

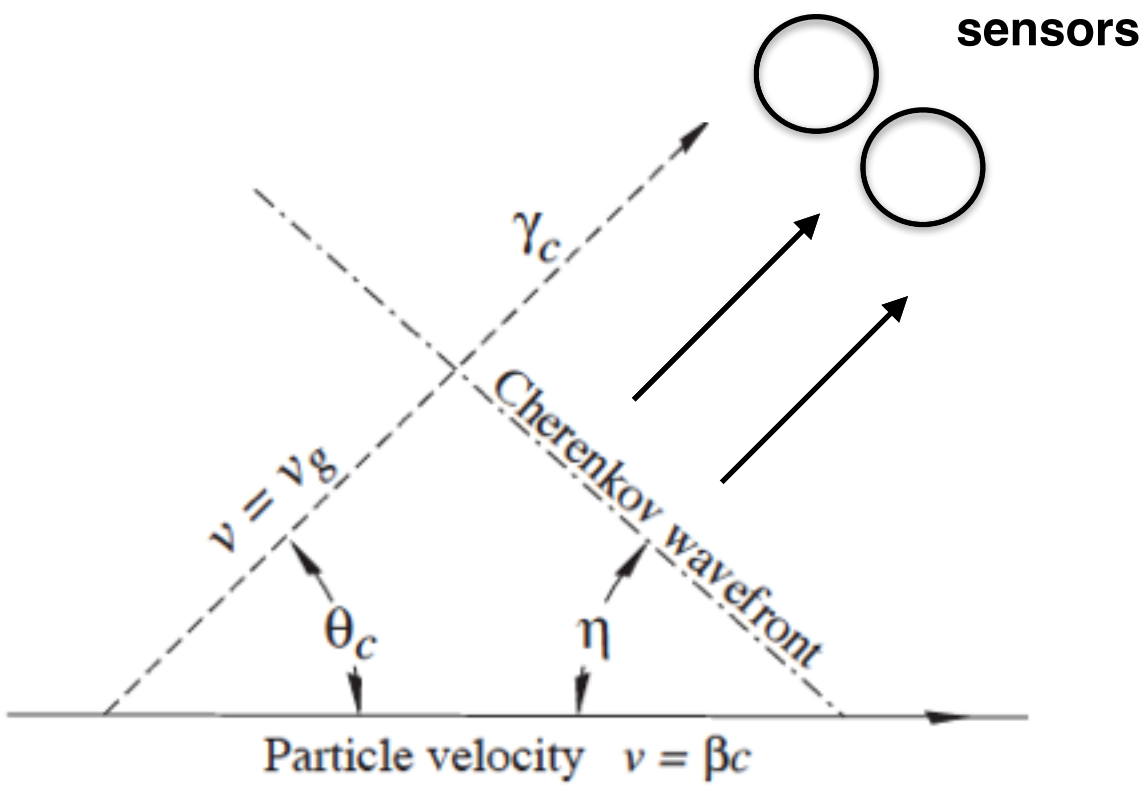
This is called ionization energy loss

Energy loss of charged heavy particles



- ***The energy loss has a minimum and rises very quickly as particle slows.***
- ***This lost energy causes to 1) free electric charge, 2) scintillation light, 3) physical (bubbles) and chemical changes (photographic plates).***
- ***Energy loss depends on velocity. At very high energies most of the loss is due to radiation (or emission of gamma rays rather than ionization).***

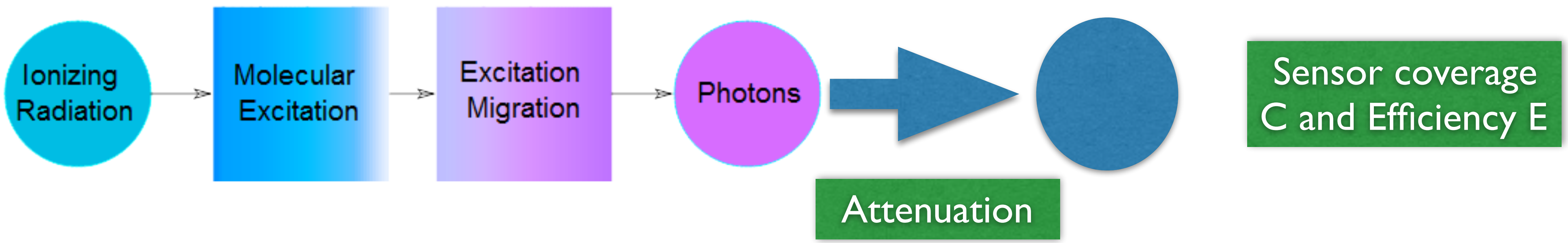
Cherenkov Radiation



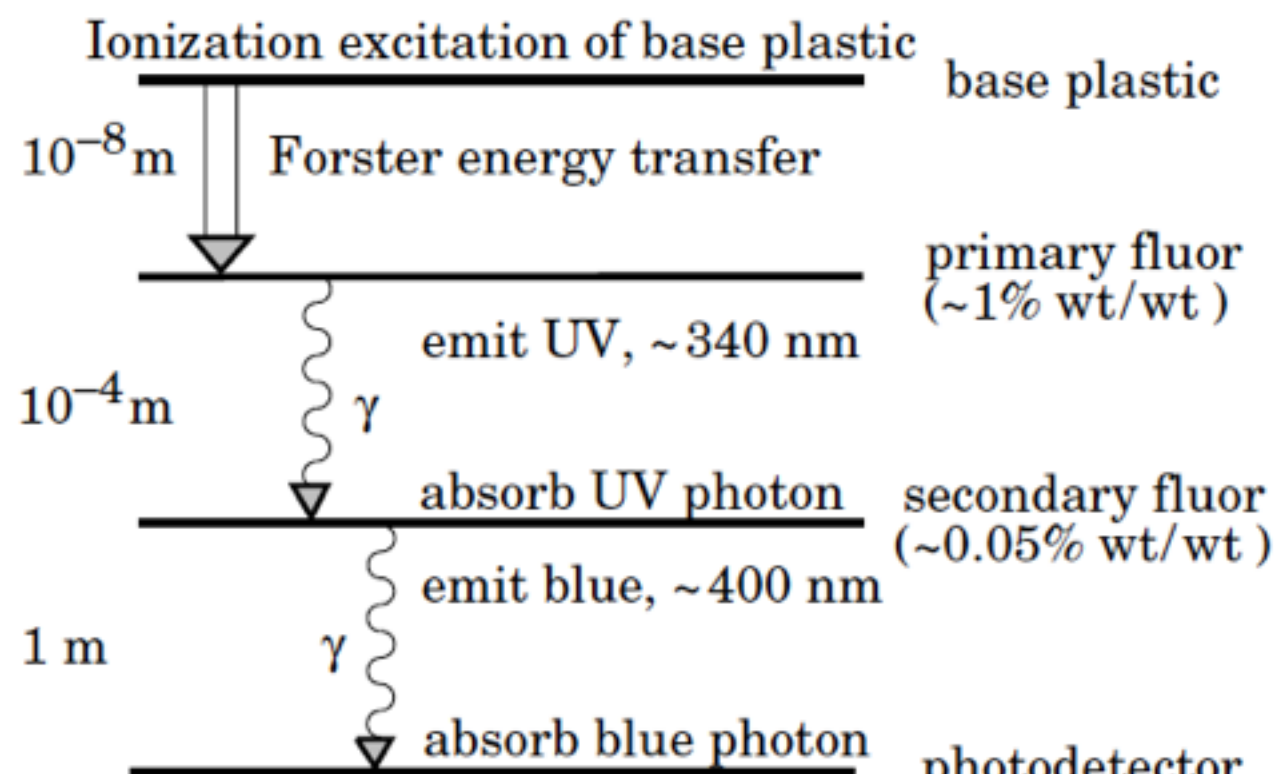
$$\cos\theta_c = (1/n\beta)$$
$$\theta_c + \eta \approx \pi/2 \quad \textit{because of dispersion}$$

- Cherenkov radiation: happens when particle moves faster than speed of light in a medium. This is used with gas, acrylic, and water.
- This radiation can be detected in sensors to reconstruct the particle. But it must have sufficient momentum to be above threshold. $\beta>1/n$

Scintillation from ionization in plastics



Time scale ~ few ns due to first fluor (rise time)

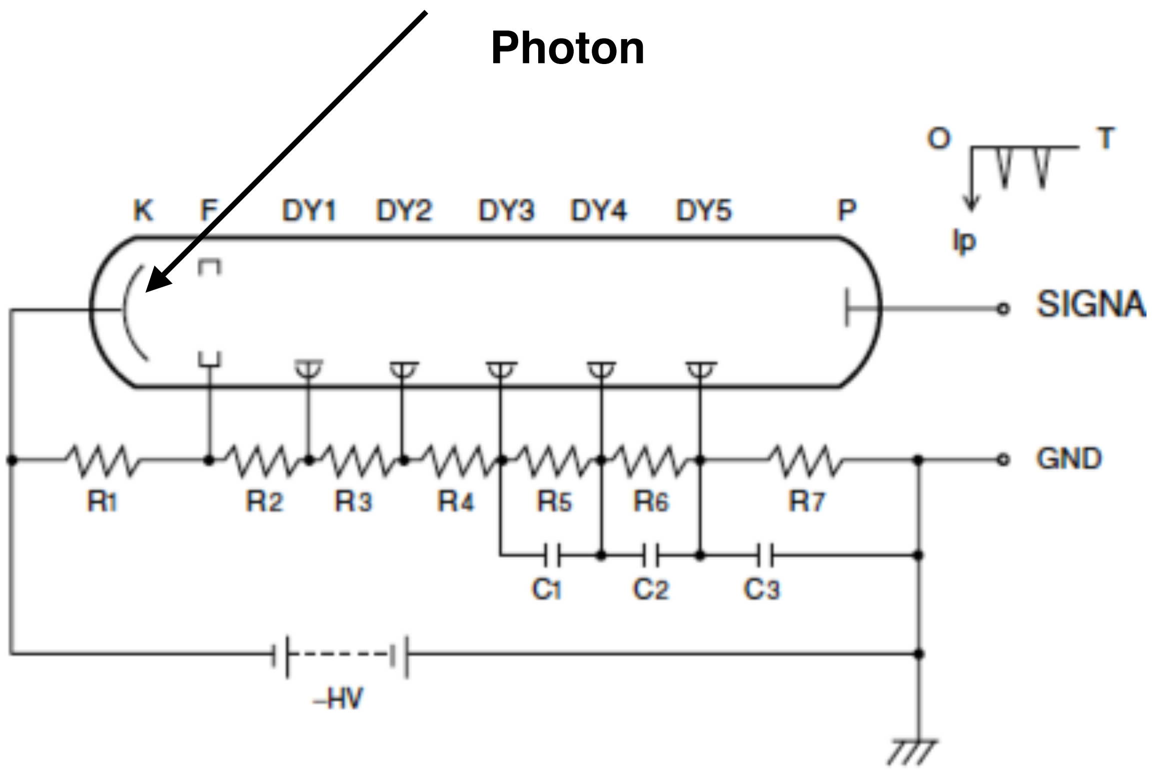


$$Typical \quad L \sim 10^4 \; photons / MeV$$

$$Yield = L \bullet C \bullet QE \bullet e^{-PathLength/\lambda}$$

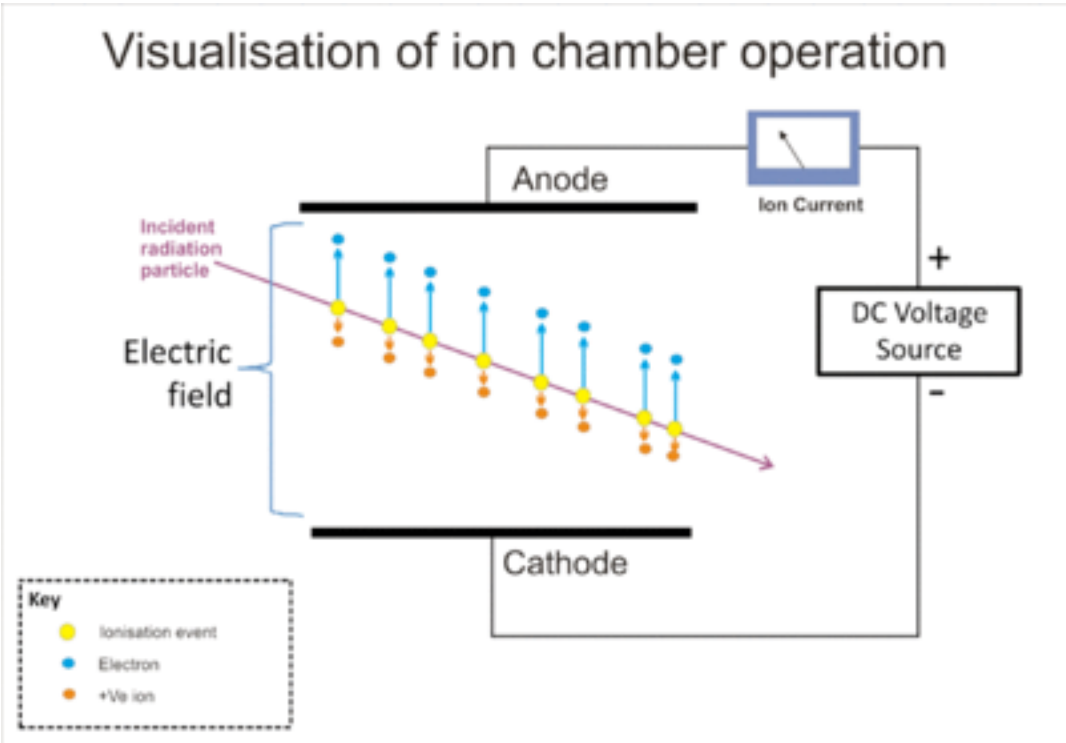
- There are many scintillation mechanisms. Organic scintillators and noble liquids are important for neutrino physics.

Photo-Multiplier Tube

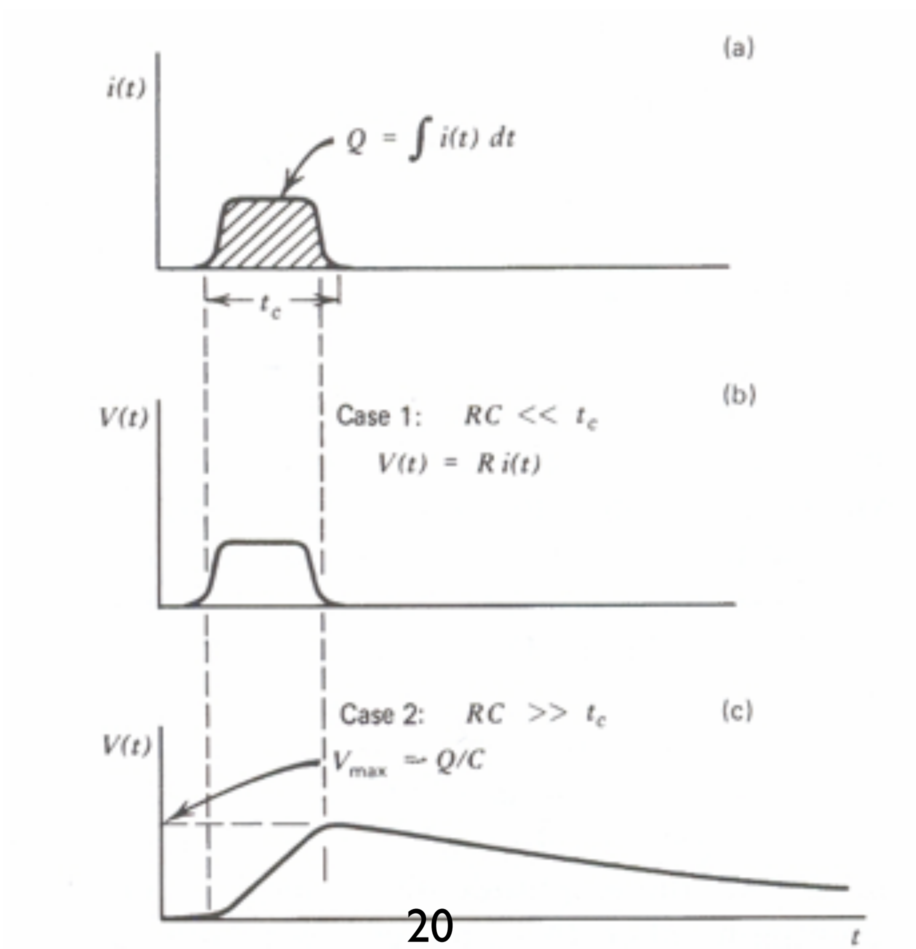


- Photons are converted to charge by a photocathode with low work function.
- Electric fields accelerate and multiply the primary electron in several stages. Each stage has multiplication of ~4-5.
- Gain can be few 10^6
- There are Many clever geometries.
- New types of photon sensors are always being developed.

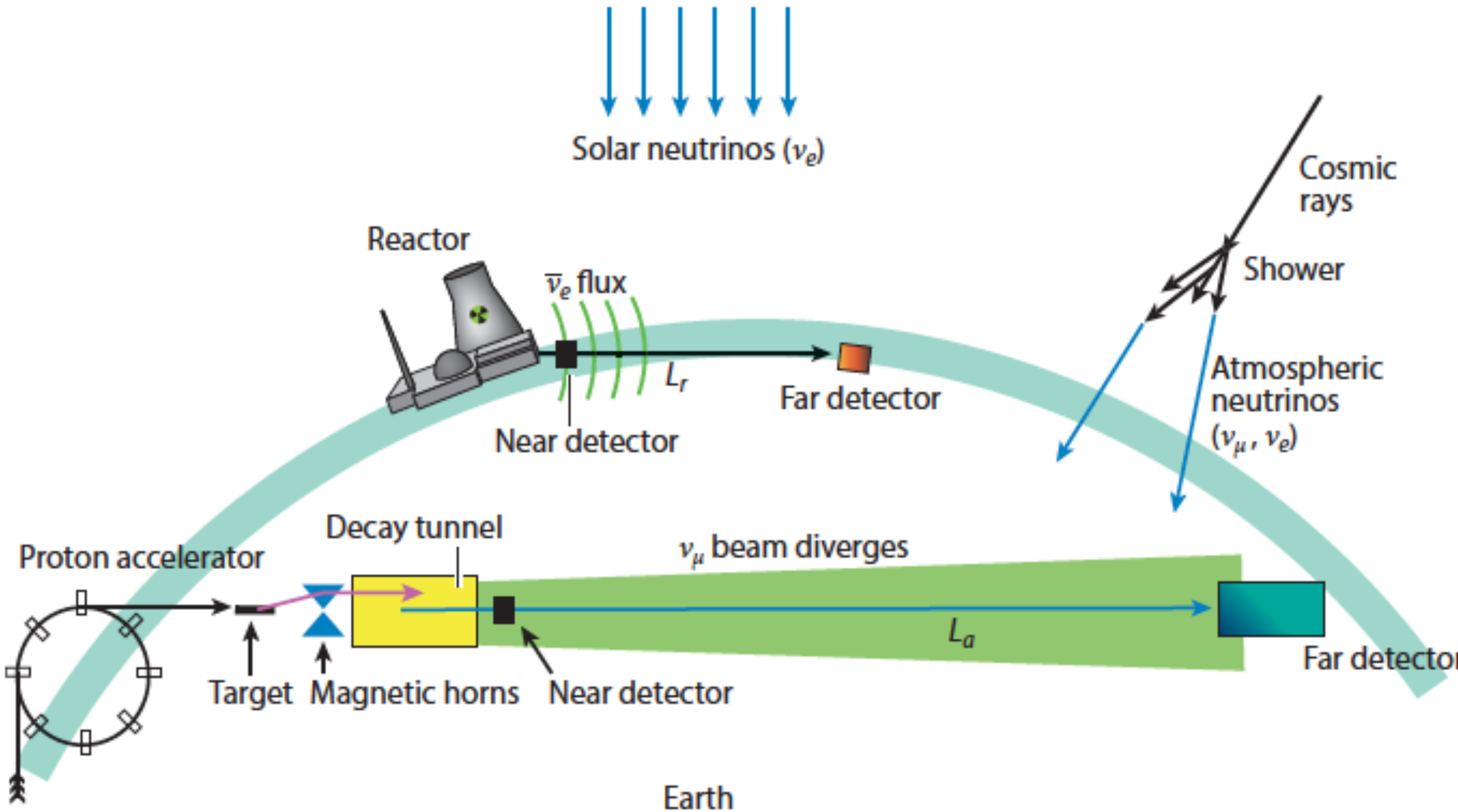
Ionization detectors



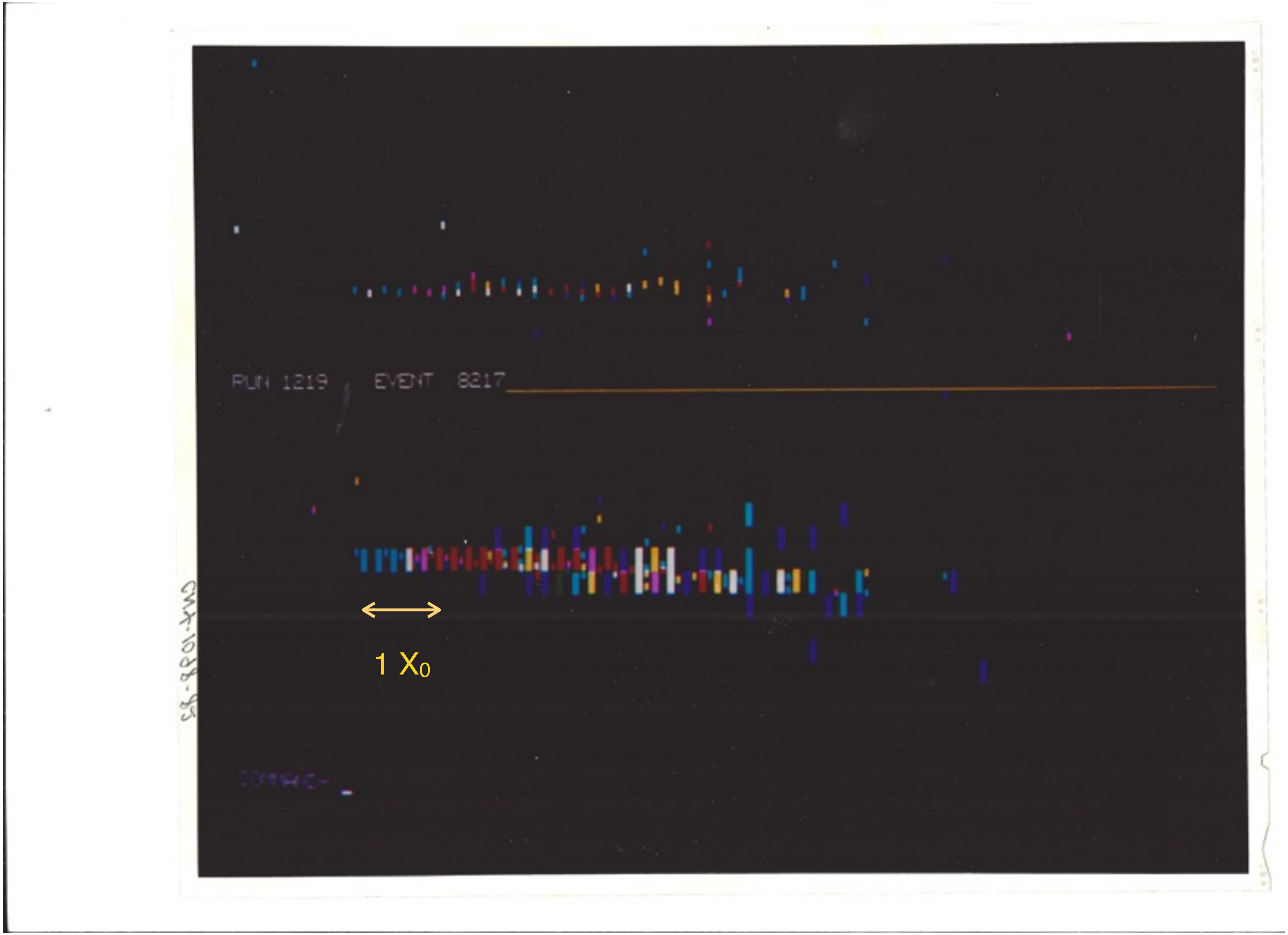
material	W (ev/pair)
LAr	23.6
LXe	15.6
Silicon	3.6
Germanium	2.9
Diamond	~13
CdTe	5.2
LNe	36
LKr	19



- In gases, semiconductors, and pure insulators, ionization creates electron-ion pairs.
- Electrons generally move about 1000 times faster than ions.
- This current can be measured as voltage across a resistor (case 1) or pulse across a capacitor (case 2)

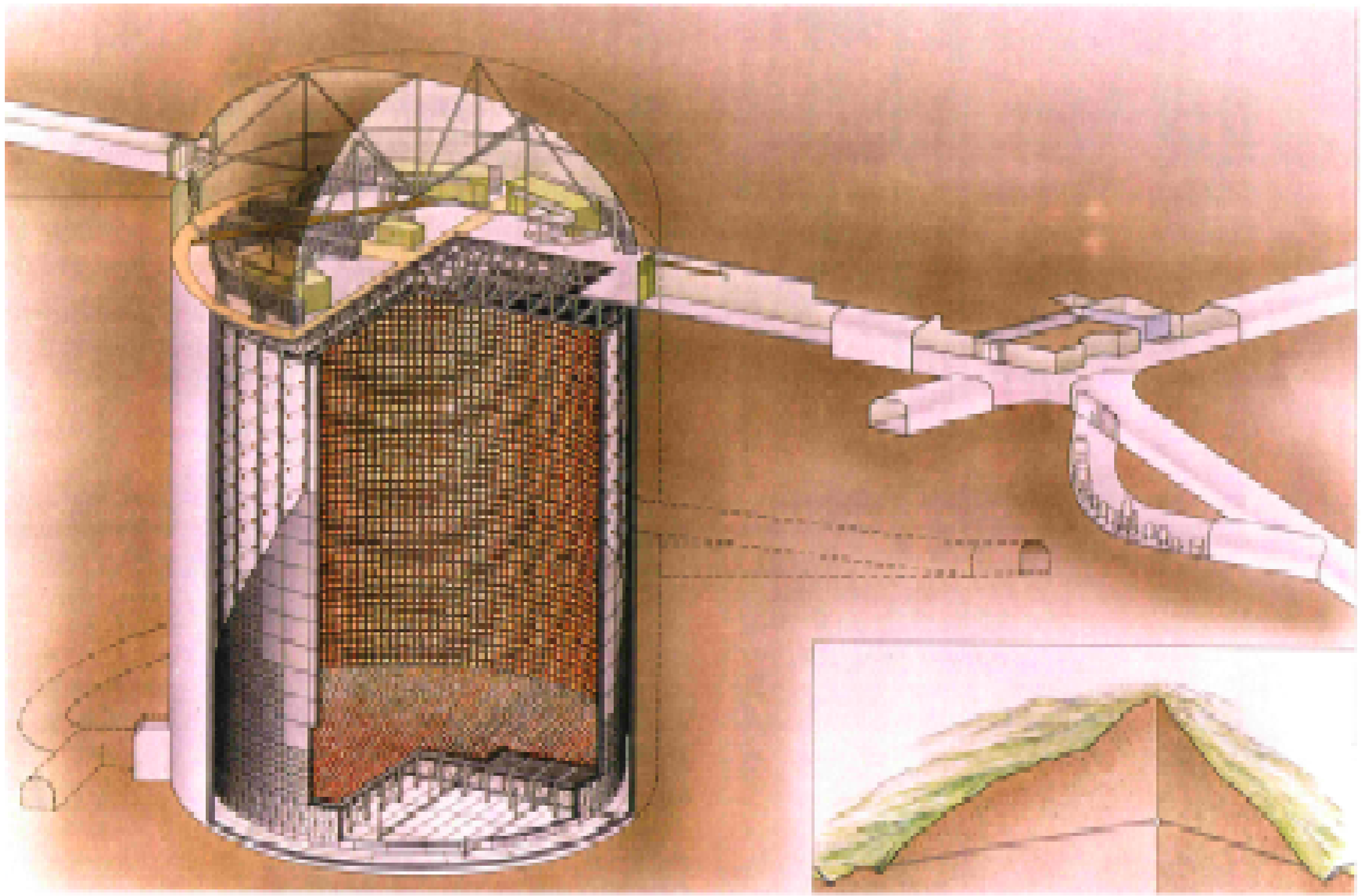


Sources of data for neutrino experiments.
Atmosphere, Solar, Accelerator, Reactor.

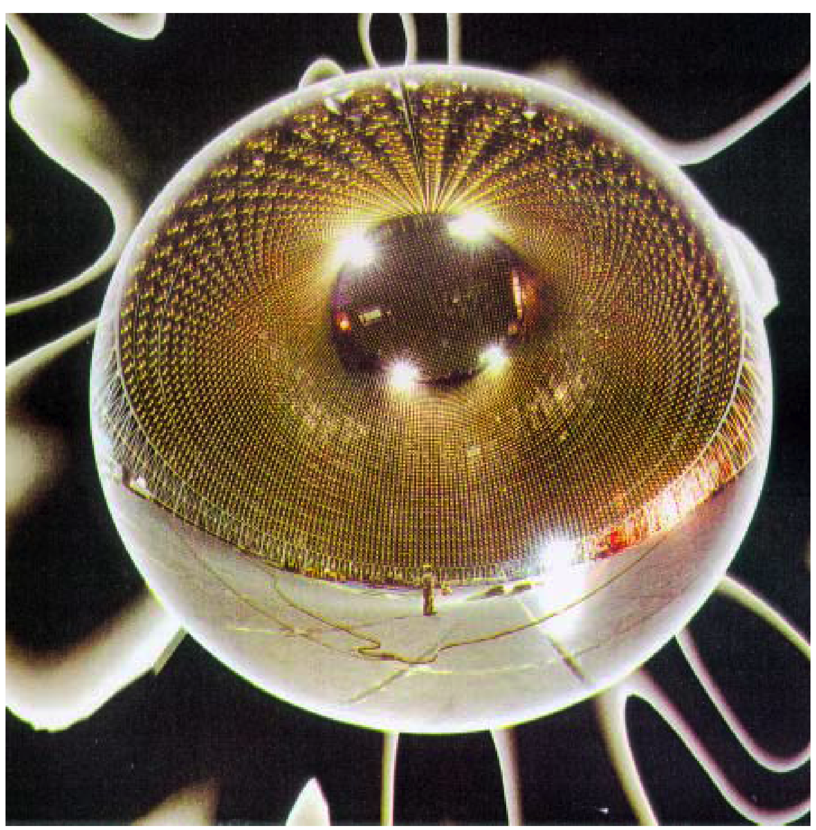


Electromagnetic shower from Experiment E734 in 1986. Example of neutrino electron elastic scattering. This is in liquid scintillator. Energy ~ 2 GeV.

Water Cherenkov SuperKamiokaNDE



Dimensions	42m(H)X39m(W)
Material	Pure Water
Attentuation	~80 m (400nm)
Total mass	40000 ton
Fiducial mass	22000 ton
inner PMTs	11146
Outer PMTs	1885
PMT dim. Inner(outer)	50 cm (20cm)
Inner coverage	~40%
Wavelength	350 nm - 600 nm



It took 4-5 years to dig and build the detector.

Ave. Depth ~ 1 km rock

Cosmic rate ~ 2 Hz

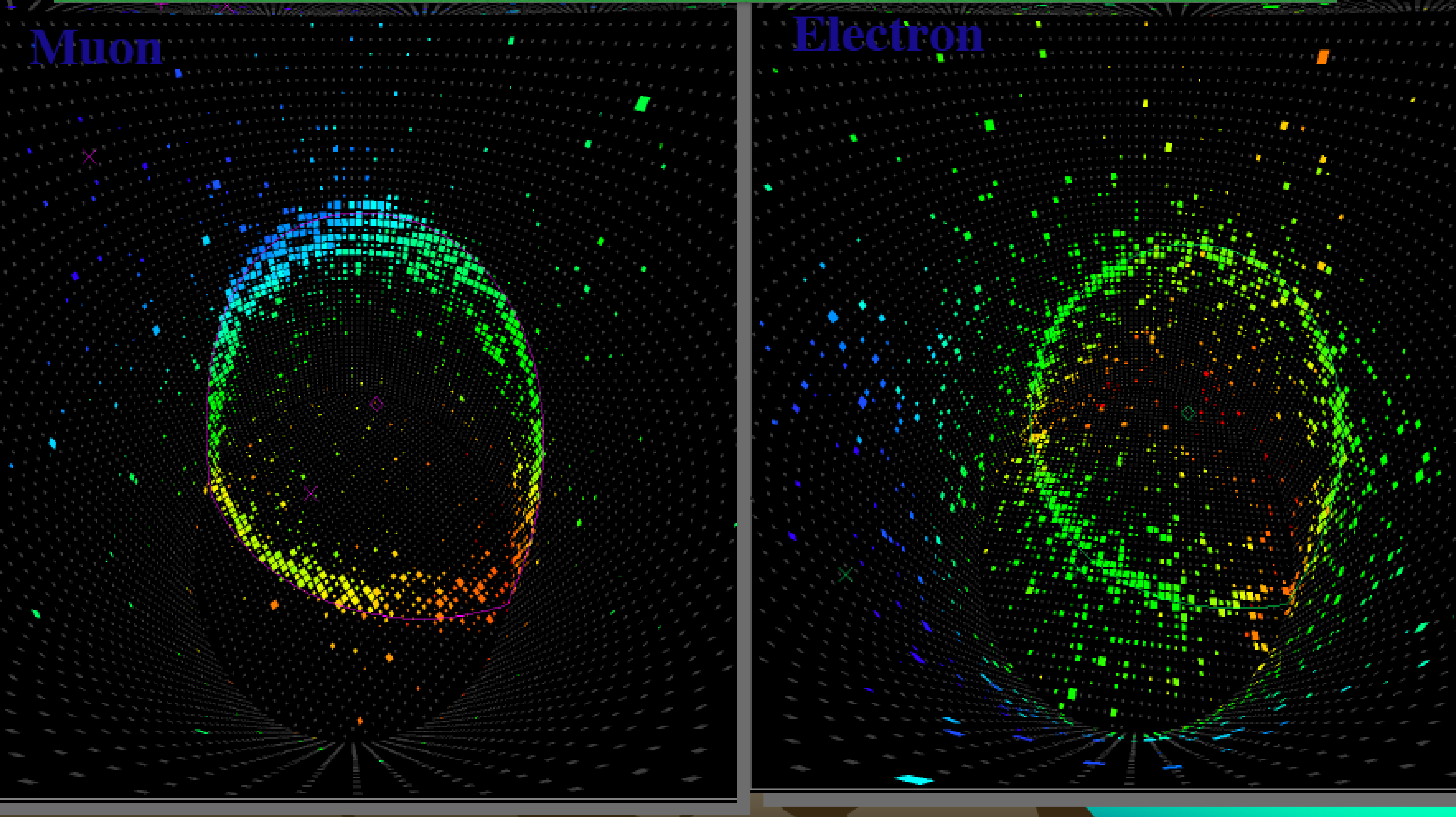
$$Yield = 370 \bullet \mathrm{Sin}^2 \theta_c \bullet \underset{\uparrow}{0.4} \bullet 0.2 \approx 10 \ pe/cm$$

Coverage X Photon detector efficiency

Technical issue: PMTs have to withstand huge pressure.

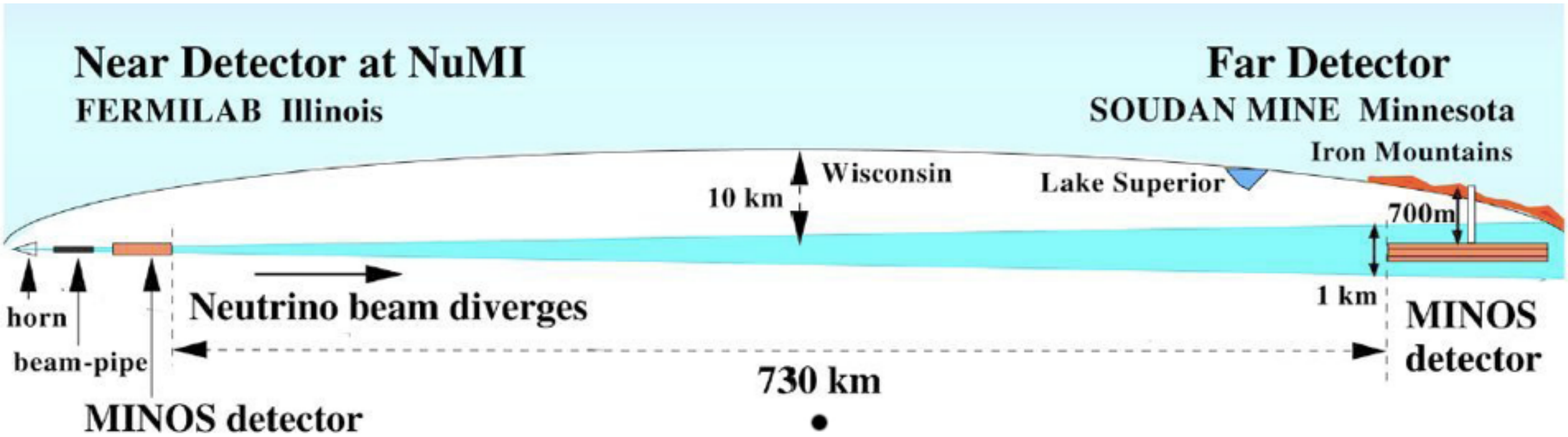
Particle Identification

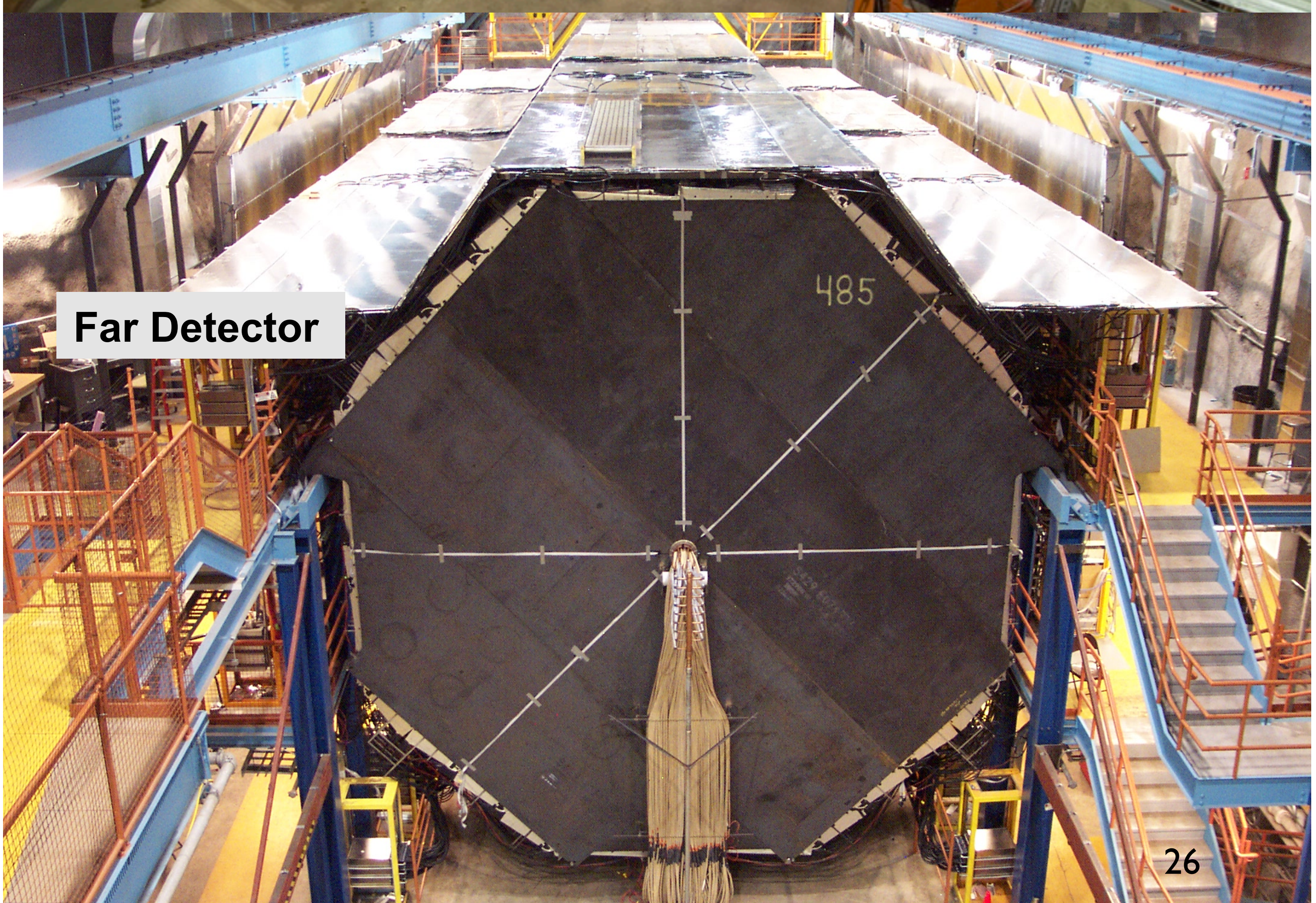
The SuperK discovered that neutrinos from the atmosphere change their flavor in flight



MINOS

- Prepare a pure beam of muon neutrino beam.
- Aim it towards a large muon detector.
- Observe spectrum of muon neutrinos to see oscillations in energy.



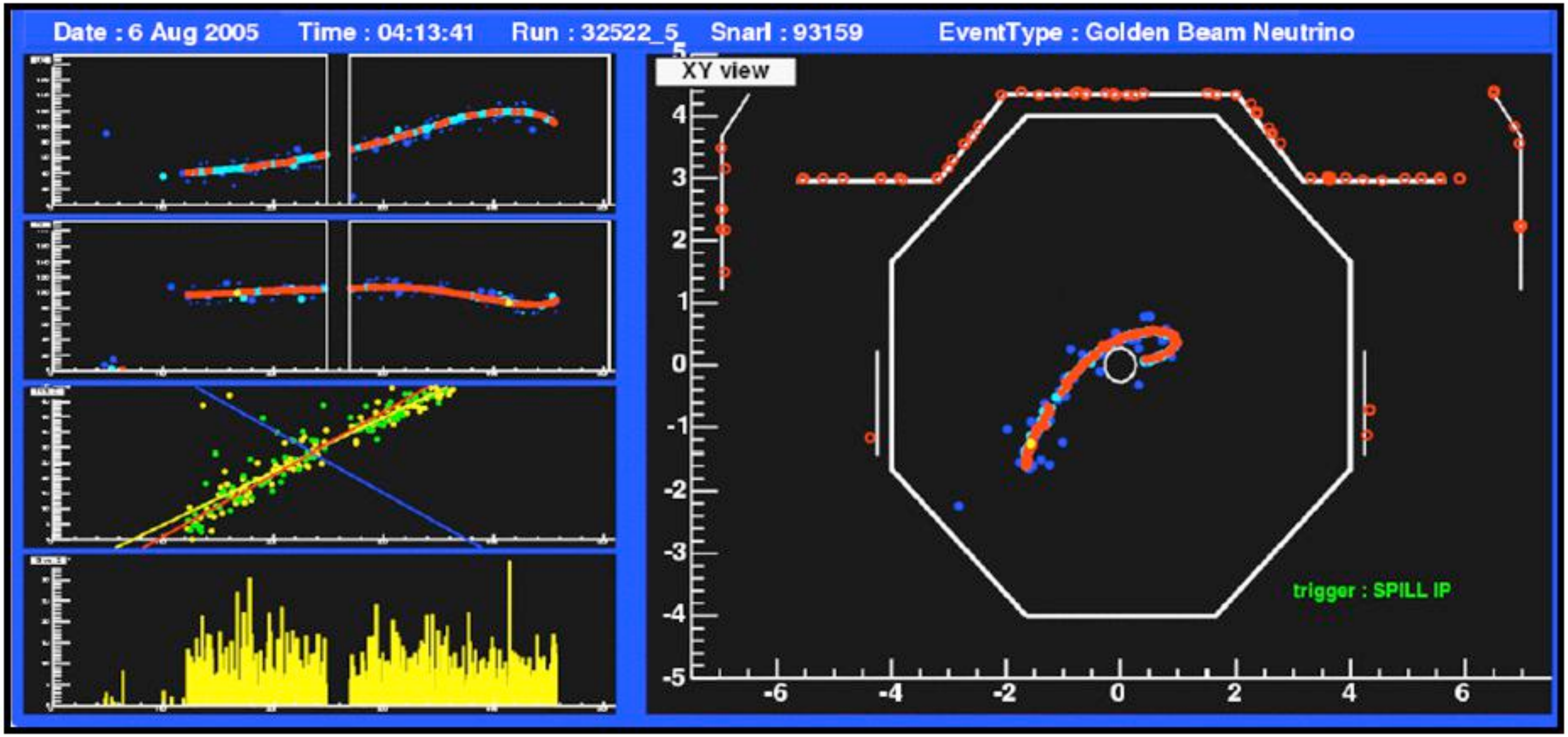


MINOS Detectors

- Massive
  - 1 kt Near detector (small fiducial)
  - 5.4 kt Far detector
- Similar as possible
  - steel planes
    - 2.5 cm thick
    - 1 Muon ~ 27 planes
    - 1.4 radiation lengths
  - scintillator strips
    - 1 cm thick
    - 4.1 cm wide
    - Molier radius ~3.7 cm

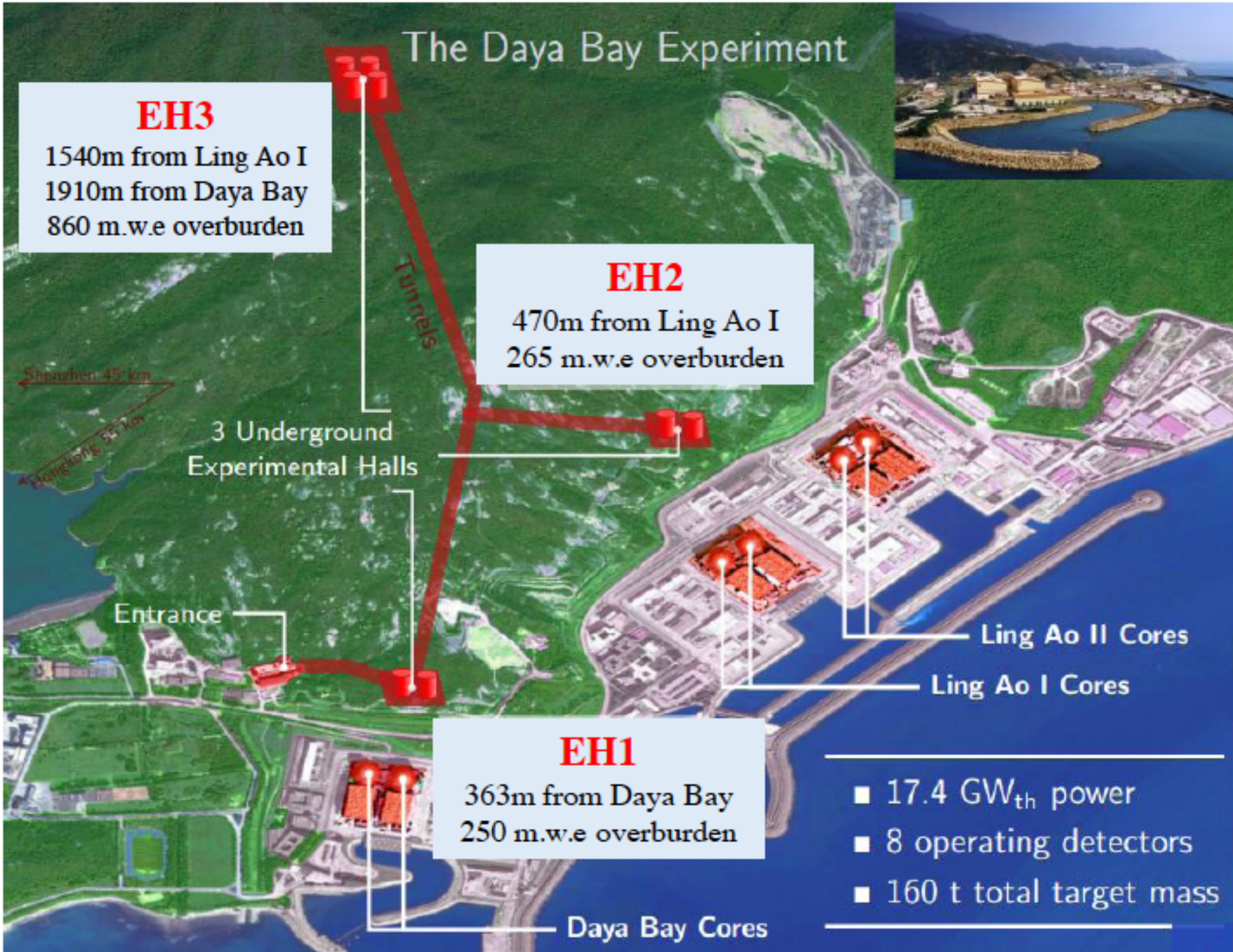
  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

Far Detector Neutrinos



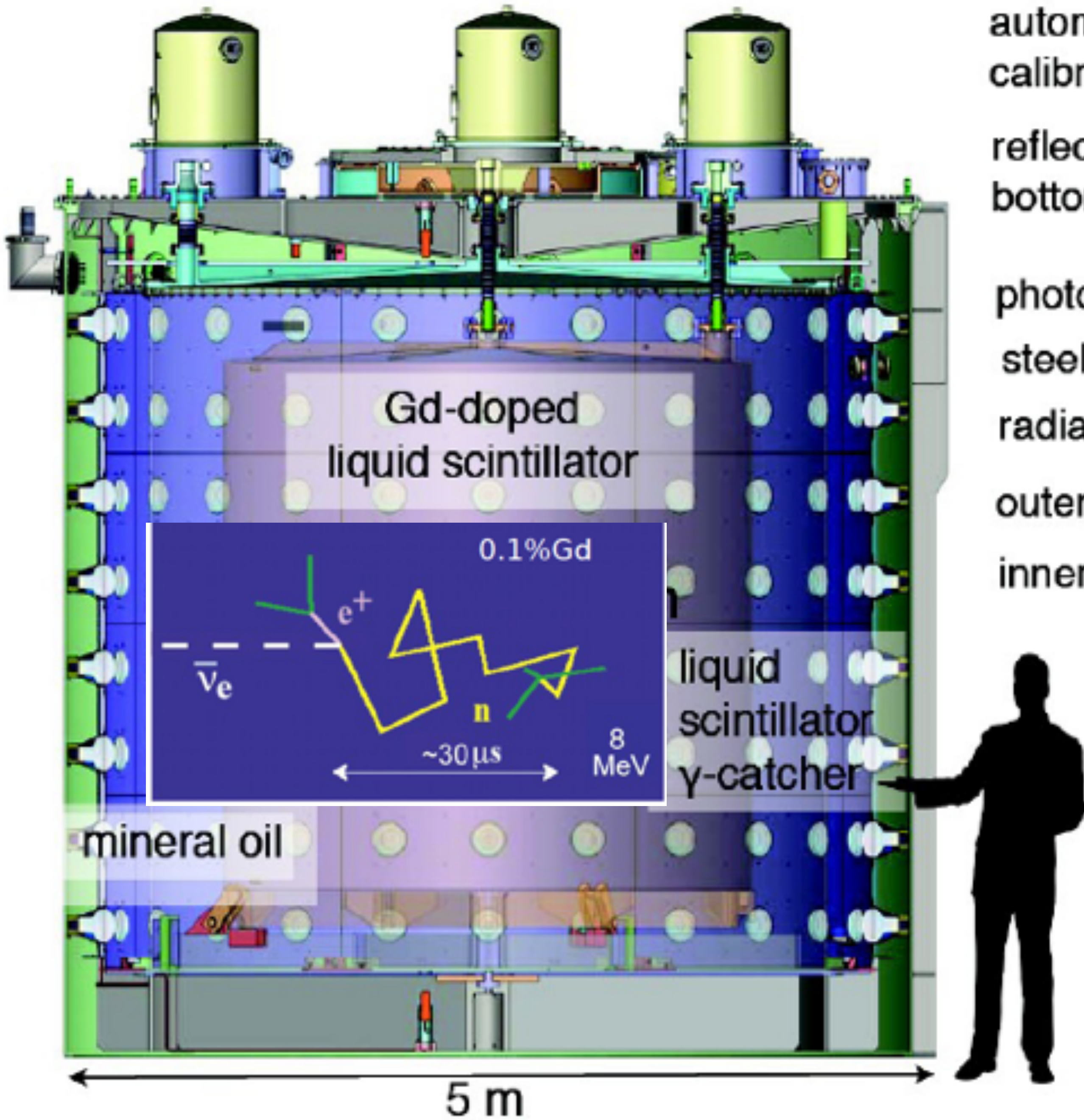
Online event display: http://farweb.minos-soudan.org/events/

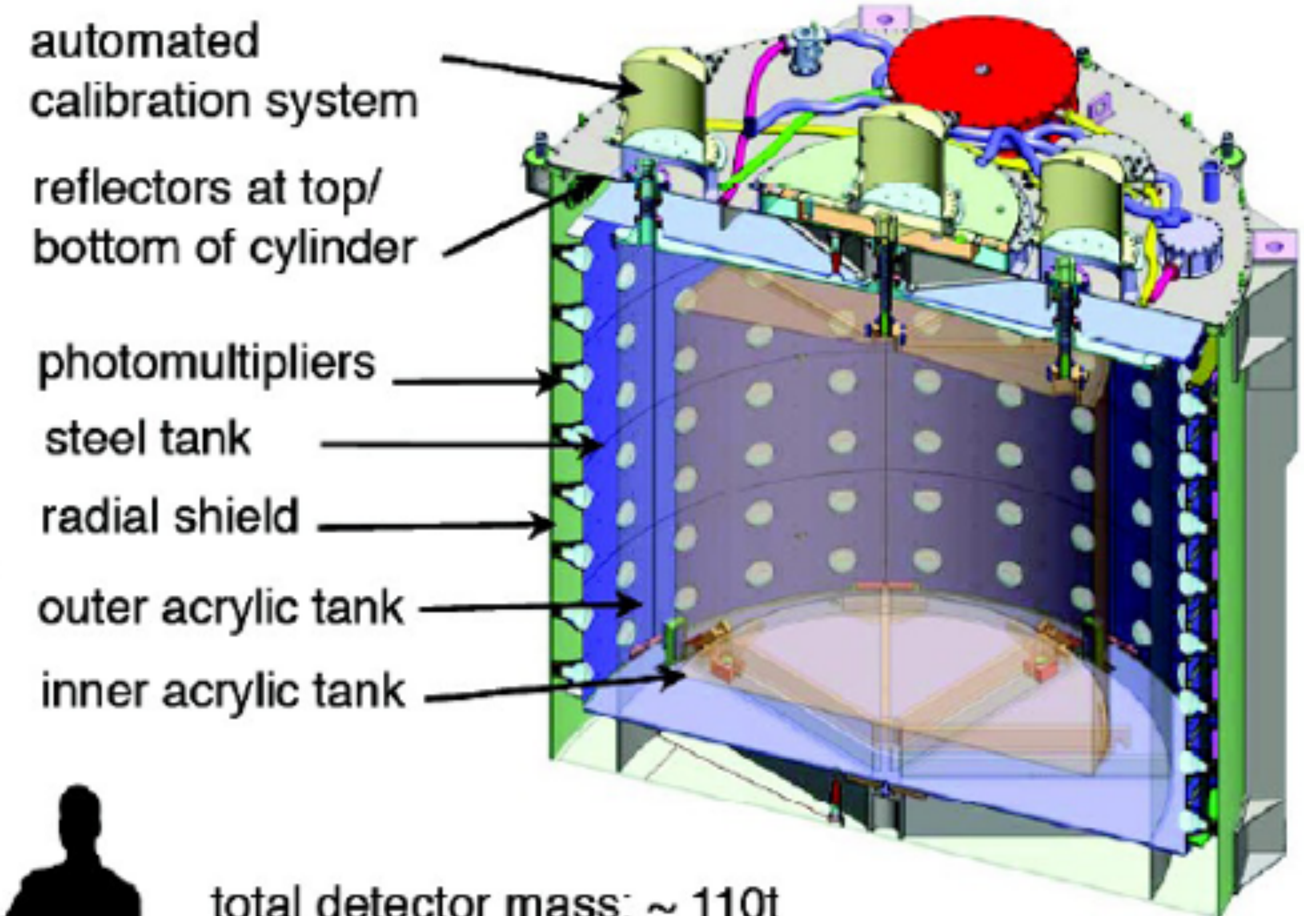
MINOS saw that muon type neutrinos disappear on their way to the far site. This allowed precise measurement of neutrino mass squared difference.



The Daya Bay Experiment
EH3
1540m from Ling Ao I
1910m from Daya Bay
860 m.w.e overburden
Tunnels
EH2
470m from Ling Ao I
265 m.w.e overburden
Shenzhen 45 km
3 Underground
Experimental Halls
Entrance
Ling Ao II Cores
Ling Ao I Cores
EH1
363m from Daya Bay
250 m.w.e overburden
Daya Bay Cores
17.4 GW$_{th}$ power
8 operating detectors
160 t total target mass

Daya Bay Antineutrino Detectors (AD)





total detector mass: ~ 110t

inner: 20 tons Gd-doped LS (d=3m)

mid: : 22 tons LS (d=4m)

outer: 40 tons mineral oil buffer (d=5m)

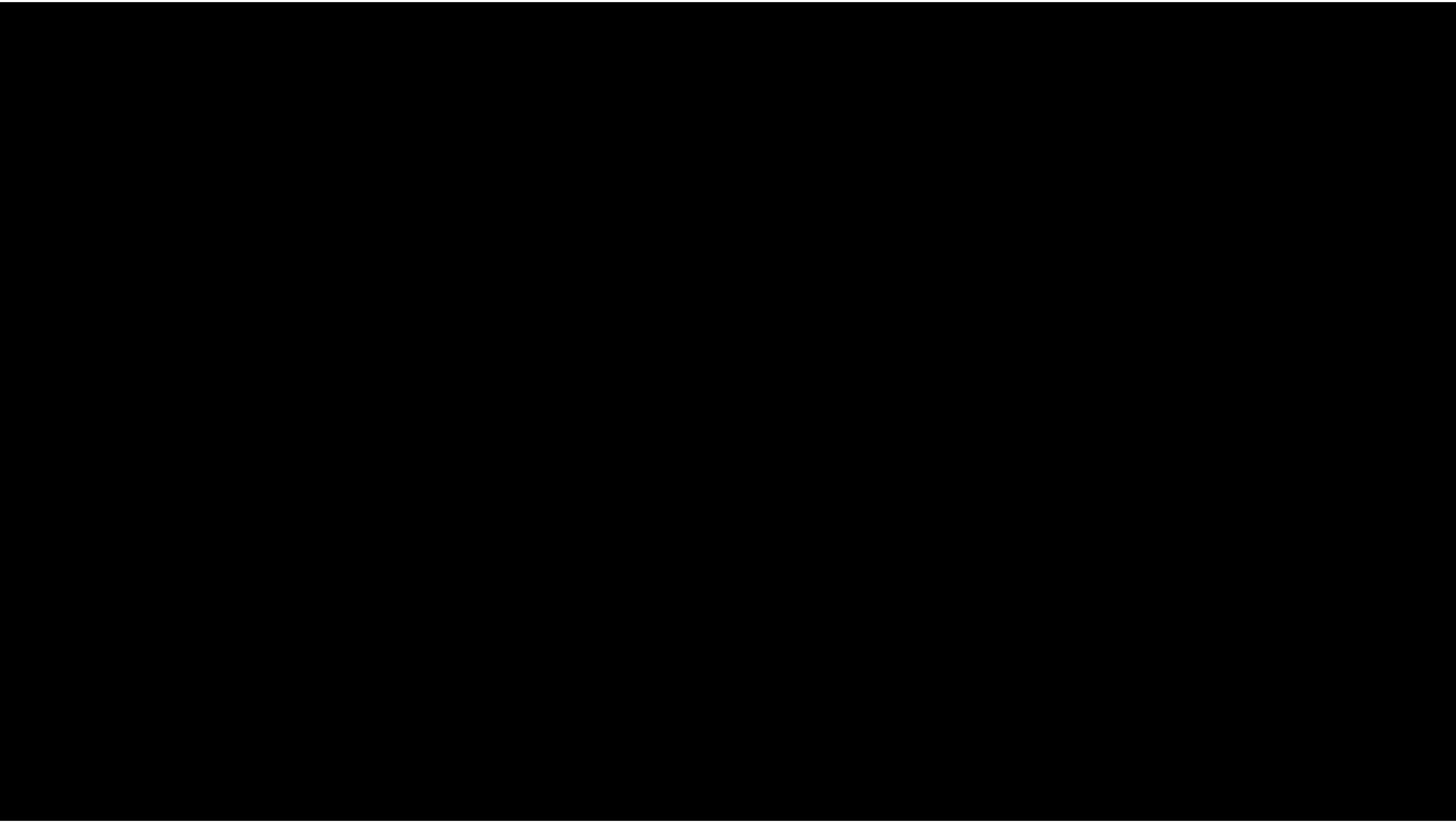
photosensors: 192 8"-PMTs

$$Yield = 10^4\,MeV^{-1} \times Coverage \times QE$$
$$= 10^4 \times 0.08 \times 0.2 \sim 160\ pe/MeV$$

8 "functionally identical", 3-zone detectors reduce systematic uncertainties.

Very well defined target region

The Future of neutrino experiments in the US



Conclusion

- This lecture was about the basics of neutrino detectors.
  - But many techniques are common for all detectors.
- Most important feature for neutrino detectors is inexpensive mass.
- Detectors are designed to measure light emission or charge deposition from neutrino interactions.
- The current motivation for neutrino detection is to study the properties of neutrinos themselves. Most important properties are mass and mixing.
- For each application additional considerations must be made
  - Energy threshold and resolution
  - Time and location measurement of events
  - Particle identification through a variety of mea